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INTERNAL BODY MOVEMENTS RESULTING FROM EXTERNALLY APPLIED SINUSOIDAL FORCES

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The Chicago Medical School

Rolf R. Coermann, Dr. Ing.

Biomedical Laboratory
6570th Aerospace Medical Research Laboratories

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6570th Aerospace Medical Research Laboratories
Aerospace Medical Division
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Wright-Patterson Air Force Base, Ohio

Contract Monitor: Rolf R. Coermann, Dr. Ing.
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NOTICES

Aerospace Medical Division,
6570th Aerospace Medical Research Laboratories, Wright-Patterson AFB, Ohio
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This report contains a description of an x-ray device designed to permit the observation of the movement of internal structures in the animal body subjected to sinusoidal oscillations. From the x-rays taken by this device, it has been possible to determine the resonance

(over)

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1. Oscillation (Sinusoidal)
2. X-Ray Photography
3. Resonance Frequency
4. Dogs (Mammals)

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FOREWORD

The information presented in this report was obtained by the Chicago Medical School, Chicago, Illinois, under Contract No. AF 33(616)-7053 for the 6570th Aerospace Medical Research Laboratories in support of Project No. 7231, "Biomechanics of Aerospace Operations," Task No. 723101, "Effects of Vibration and Impact." The responsible investigator in this research was Dr. John L. Nickerson, Chicago Medical School. In this work he had the active assistance of A. Paradijeff, M.D., M. Drazic, M.A., C. Gannon, B.Sc., J. Greenman, B.Sc., G. Nemhauser, B.Sc., V. Steiner, B.Sc., J. Wolter, B.Sc., and R. Satzman. The research contained in this report was accomplished between March 1960 and December 1961. Dr. R.R. Coermann, of the Vibration and Impact Section, Bioacoustics Branch, Biomedical Laboratory, 6570th Aerospace Medical Research Laboratories, served as contract monitor.

Animal experimentation reported herein was performed in accordance with "Principles of Laboratory Animal Care" established by the National Society for Medical Research.

ABSTRACT

This report contains a description of an x-ray device designed to permit the observation of the movement of internal structures in the animal body subjected to sinusoidal oscillations. From the x-rays taken by this device, it has been possible to determine the resonance frequency and phase shift of regions within the abdomen and thorax set in motion by external oscillatory forces. The results of observations made on anesthetized dogs show that the visceral content of the abdomen and thorax appears to oscillate as a mass having a resonant frequency of 3 to 5 cycles per second and with damping of one-fifth to one-quarter of the critical value.

PUBLICATION REVIEW

This technical documentary report has been reviewed and is approved.

Jos M Quashnock

JOS. M. QUASHNOCK
Colonel, USAF, MC
Chief, Biomedical Laboratory

TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

TABLE

INTERNAL BODY MOVEMENTS RESULTING FROM EXTERNALLY APPLIED SINUSOIDAL FORCES

INTRODUCTION

The effects of mechanical vibration on man have been for many years a subject of interest (refs. 1-13) and in recent years with increased mechanized speed in man's environment the subject has become of considerable practical importance. Recently (ref. 12), measurements on the human subjected to oscillatory forces have permitted determination on the resonance response of various regions of the human body. Simultaneous observation of human tolerance to the shaking stresses at various amplitudes, frequencies, and body positions have been made. These studies have shown in general that tolerance to shaking stress is least when the applied frequency is close to the resonance frequencies of various body structures. A preliminary report of the present research was made in 1961 (ref. 14).

EXPERIMENTAL METHODS

The objective of this research was to investigate the effects of externally applied sinusoidal movements on organs within the animal body. The observations made were planned to provide information on the relative movement of organs in the body. The specific work reported here was performed on anesthetized dogs.

The sinusoidal movements for this experimental work were produced by the use of an L.A.B. VU-DM-100 vibration test stand. This instrument enabled one to provide oscillations of frequencies between 1 and 60 cycles per second with amplitudes ranging from 0 to 12-1/2 millimeters double amplitude. The instrument itself had a mechanical limitation in that no more than 10 G's were to be produced and applied at any time. The number of G's produced in the sinusoidal oscillation depend upon the amplitude and frequency of the oscillation. Figure 1, on next page, shows this relationship in a graphical manner so that when given the millimeters of double amplitude and the frequency of the oscillation in cycles per second the number of G's produced by the oscillation can be read from the graph. This graph also shows the range not to be entered upon for the particular vibration test machine used.

After early experiments it was found that at low frequencies sufficiently large g forces were not attainable at the maximum double amplitude of 12.5 mm. Therefore, a mechanical amplifier was devised to increase the maximum double amplitude of 12.5 mm to 54 mm. This system is illustrated in figure 2, on next page. As before the instrumental limitation on frequency and amplitude was determinable from figure 1.

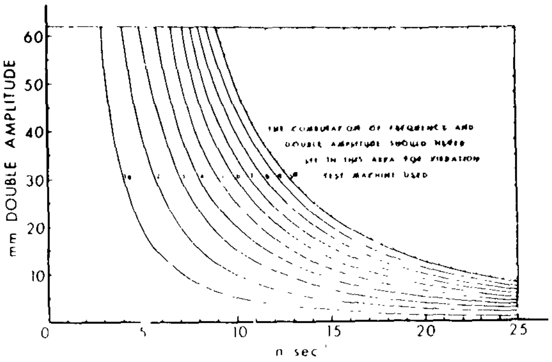

Figure 1. G-Value Determination from Frequency and Amplitude

Graph used in determining G's produced in any sinusoidal vibration test when the double amplitude and frequency of the vibration are known.

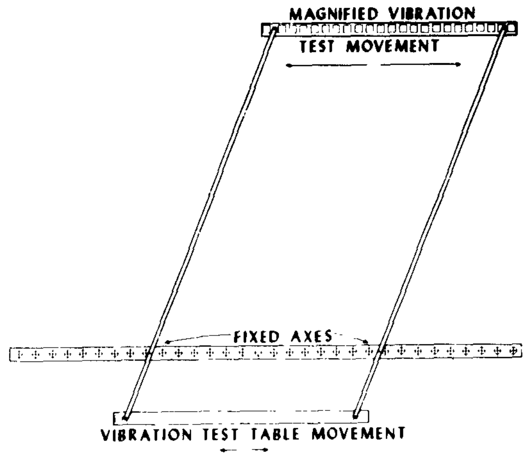

Figure 2. Amplitude Magnifier.

Diagram to illustrate the magnification in amplitude of the vibratory movement. The test movement amplitude is many times the vibration table movement.

The method for determining the magnitude of movement of regions within the animal body was dependent upon the use of x-rays. This method is illustrated in figure 3. Radio opaque objects were sutured to structures within the animal body and the animal securely fastened in a plastic trough mounted on the vibration test stand. As the animal was shaken along its longitudinal axis across the beam of x-rays the opaque objects cast moving shadows upon a photographic film. A still picture taken with the animal at rest in the cradle enabled one to locate the position of the opaque objects relative to the reference grid system. This is illustrated in figure 4 on the next page. The type of picture is shown in figure 4. Next a slit in a leaded screen was so

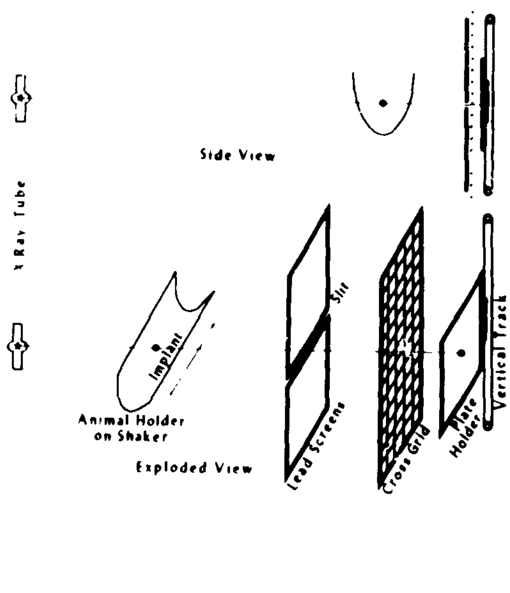

Figure 3. Arrangement for X-ray Kymography.

Diagrams to illustrate the formation of the x-ray shadow of an implanted object. Horizontal movement of the shadow along the slit in lead screen, and vertical movement of the photographic plate will combine to form a trace indicating the movement of the opaque object within the animal.

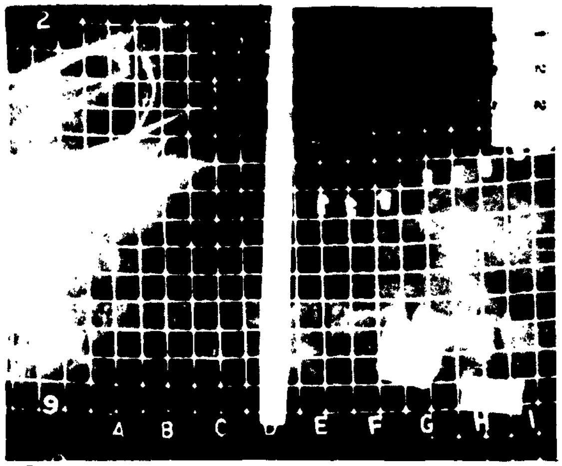

Figure 4. X-ray Location of Implant.

An x-ray picture of the animal. The lead screen containing the slit has been removed for this procedure. The grid system which permits locating the objects implanted in the animal and the long reference rod attached to the vibration test table are shown in this picture.

located that the shadow of one or more of the opaque objects as well as the long reference rod fell upon the slit so that when movement of the animal was initiated the shadow moved back and forth across the slit throwing a moving shadow upon the photographic film and subjecting the film to exposure along a narrow line. The photographic film now was moved at a steady speed in a direction at right angles to the slit and in a plane perpendicular to the x-ray beam. The shadow of the opaque object followed an oscillatory path representing the movement of the opaque object within the body. Therefore, there was traced upon the photographic film an exact record of the movement of the opaque object relative to the ground. This is illustrated in figure 5 on the next page. In figure 5 there appears also the shadow tracing of a steel reference rod attached to the vibration test table. The relative movement of vibration tester and opaque object is immediately apparent. Since the exact dimensions of the reference rod and implants were known, a simple proportional calculation permitted determination of the exact double amplitude (peak to trough) of the movement of the shaker and of the implants. The ratio of the double amplitude of movement of the implant to the double amplitude of the shaker was computed for each frequency and the ratio designated as the amplitude magnification.

It was also a simple calculation to determine the phase lag of the implant oscillation to the shaker oscillation. The upper edge of each tracing was a line of simultaneity. If the distance from this edge to the first peak of the opaque object was "a" mm, the distance of the first peak of the reference rod "b" mm and the wave length (peak to peak) "c" mm, then the phase lag was computed from the relationship

$$\theta = \frac{(a-b)}{c} \times 360 \text{ degrees.}$$

The implanted radio-opaque objects were specially constructed to have the density of the tissues in which they were implanted. Matching of implant and tissue density minimized local tissue contusion by the moving implant during the oscillation tests and eliminated the effect of inertia on the movement of the implant. Average values of the density of fresh tissues are given in table I on page 5. The opaque objects were constructed of cylindrical shells

Figure 5. X-ray Kymograph.

An x-ray picture demonstrating the vibratory movement of shaken rod (smaller amplitude) and the two opaque objects shown in figure 4. Figure 5 is taken with the lead screen containing the horizontal slit in its functioning position.

of stainless steel or tantalum of approximately eleven thousandths of an inch thick. The metal shells were filled with wax impregnated cork. The combination of metal and cork was adjusted to give adequate radio-opacity and possess density values between 1.00 and 1.08. The objects had linear dimensions of the order of 10 to 12 millimeters. Stainless steel implants were satisfactory for acute tests but tantalum implants were used for long term tests.

The size of the object had a direct bearing on the contrast between its shadow and the background on the photographic plate. Consider the following argument: let the photographic plate speed be $\underline{v}$ centimeters per second, the slit width $\underline{s}$ centimeters, the width of the implant $\underline{w}$ centimeters, the double amplitude of the oscillation $\underline{d}$ centimeters and the frequency $\underline{n}$ cycles per second. Then in order that a point on the film remain in the shadow of the horizontally moving implant as the photographic plate moves vertically through a distance equal to the width of the slit, the following relationship must hold:

$$w \geq (\pi\ d\ n)\left(\frac{s}{v}\right)$$

By experimental test the contrast remained adequate when

$$w \geq \frac{2dns}{v} .$$

In the apparatus used, s = 1.5 mm and v = 63 mm/second so that for the case where d = 25 mm and n = 10 cycles per second,

$$w \geqslant 12 \text{ mm}.$$

When the implant width was considerably less than the values computed according to the equation above, the peaks and troughs were still clearly defined but the general wave form was difficult to distinguish because of lack of contrast throughout a complete cycle.

TABLE I

DENSITY OF FRESH TISSUES OF THE DOG* IN GMS/CC.

1.	Skin	1.01
2.	Ligament	1.06
3.	Diaphragm	1.07
4.	Lung	1.08
5.	Trachea	1.05
6.	Aorta	1.07
7.	Heart	1.06
8.	Spleen	1.07
9.	Kidney	1.05
10.	Urinary Bladder	1.06
11.	Adrenal	1.05
12.	Esophagus	1.08
13.	Fundus of Stomach	1.04
14.	Pyloris	1.05
15.	Duodenum	1.04
16.	Liver	1.07
17.	Gall Bladder	1.06
18.	Pancreas	1.08
19.	Small Intestine	1.08
20.	Colon	1.07

* Average of data obtained by V. Steiner

THEORY RELATING TO MOVEMENT OF SHAKEN MASSES

The opaque object can be considered as a mass suspended upon a spring and damper. The quantities measured in the investigation were the displacement (x) of the shaker or suspending point and the displacement (y) of the opaque object or mass. The following equation describes the relationship between x and y.

$$m\ddot{y} + c(\dot{y}-\dot{x}) + k(y-x) = 0 \tag{1}$$

$$\text{or} \quad m(\ddot{y}-\ddot{x}) + c(\dot{y}-\dot{x}) + k(y-x) = -m\ddot{x} \tag{2}$$

The solution of this equation can be written

$$y-x = \frac{x(n/n_o)^2}{\sqrt{[1-(n/n_o)^2]^2 + [2\delta(n/n_o)]^2}} \tag{3}$$

This expression indicates the amount of strain imposed on the tissues suspending the shaken organ to which the opaque object is attached.

The strain relative to vibration table displacement is given by

$$\frac{y-x}{x} = \frac{(n/n_o)^2}{\sqrt{[1-(n/n_o)^2]^2 + [2\delta(n/n_o)]^2}} \qquad (4)$$

The phase lag between (y-x) and x is

$$\phi = \tan^{-1}\frac{2\delta(n/n_o)}{1-(n/n_o)^2} \qquad (5)$$

Graphical representation of equations 4 and 5 is presented in figures 6 and 7.

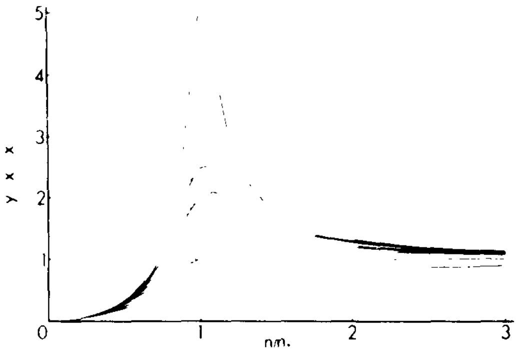

Figure 6. Relative Movement of Implant and Shaker.

Graph of equation 4. This figure shows the relative movement of shaken object and vibrator (y-x) to the movement of the vibrator (x) as a function of the ratio of the impressed frequency/resonance frequency (n/n_o).

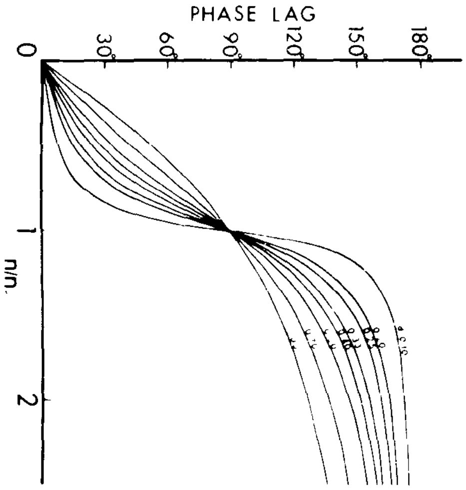

Figure 7. Phase Lag of Relative Movement of Implant and Shaker.

Graph of figure 5. Phase lag between the relative movement of shaken object and vibrator (y-x) and the vibrator (x), as a function of the ratio of the impressed frequency/resonance frequency (n/n_o).

The amplitude magnification, that is, the ratio of the mass-displacement to the table displacement is

$$\frac{y}{x} = \frac{\sqrt{1 + [2\delta(n/n_o)]^2}}{\sqrt{[1 - (n/n_o)^2]^2 + [2\delta(n/n_o)]^2}} \qquad (6)$$

and the phase lag between y and x is

$$\phi = \tan^{-1}\frac{2\delta(n/n_o)^3}{(n/n_o)^2\ (1-4\delta^2)\ -\ 1} \tag{7}$$

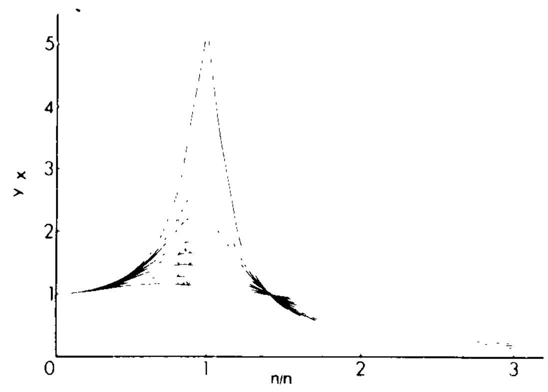

Figure 8. Relative Amplitude of Implant and Shaker Movement.

Graph of equation 6. This figure shows the relative amplitude of movement of the shaken object (y) to the movement of the vibrator (x) as a function of the ratio of the impressed frequency/resonance frequency (n/n_o).

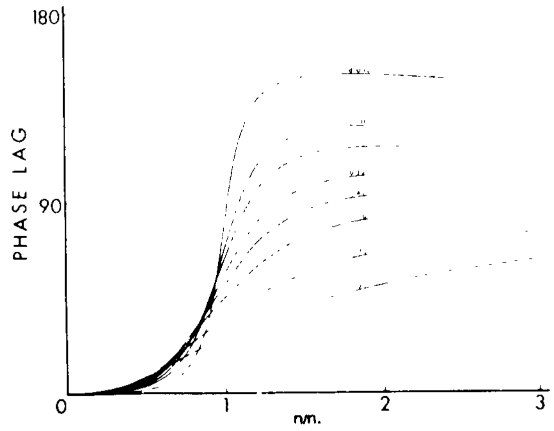

Figure 9. Phase Lag of Relative Amplitude of Implant and Shaker Movement.

Graph of equation 7. This figure shows the phase lag between the movement of the shaken object (y) and of the vibrator (x) as a function of the ratio of impressed frequency/resonance frequency (n/n_o).

In these equations the symbols have the following meaning:
x = displacement of the suspending point (vibration test table)
y = displacement of the mass (m)
n = frequency of the vibration test table
$n_o = \sqrt{k/m}$ = natural frequency of the undamped mass-spring system
k = spring gradient
c = viscous damping factor
$\delta = c/c_c$ = damping coefficient
c_c = critical damping factor = $2mn_o = 2\sqrt{km}$

From the equation for the amplitude magnification, equation 6, there can be deduced by differentiation the condition for the value of (y/x) at the peak of the response. This relationship is given by

$$[n/n_o]^2 = \frac{\sqrt{(1+8\delta^2)}\ -\ 1}{4\delta^2} \tag{8}$$

With this equation and equation 6 the interrelation of (y/x), (n/n_o) and δ at the peak can be determined. These interrelations are shown graphically in figure 10 on next page.

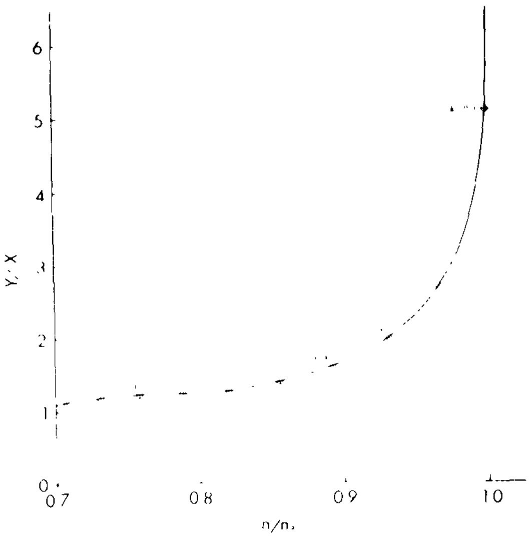

Figure 10. Graph for Determining Reson-Frequency and Damping of the Oscillating System.

Graph of equation 8. When the data on a specific test is plotted as amplitude magnification (y/x) against the frequency (n), the value of (y/x) and (n) and the point of the maximum can be determined. Figure 10 then enables one to obtain from the value of (y/x) at the maximum the damping factor δ and the value of the ratio n/n_o, and, hence by computation the value n_o.

In evaluating the data from the experiments the following was the procedure. From x-ray pictures like figure 5 the amplitude of the movement of the opaque object (y) and reference rod (x) were determined in mm corrected to the value within the animal and at the shaker respectively. The ratio y/x was plotted against the frequency which was recorded when the x-ray picture was taken. The results of a number of experiments are shown in figure 11. In this figure the peak of the response is approximately at 3.5 cycles per second and the value of the amplitude magnification approximately 2.6. From the curve in figure 10 one can determine that for this value of amplitude response the value of n/n_o is 0.963. Therefore, the frequency n_o has the value $n_o = 3.5/0.963 = 3.6$ cycles per second. Similarly, from the curve in figure 10 the damping coefficient has a value of approximately 0.22.

RESULTS

The results of these experiments are illustrated in the figures. Figure 11, on next page, also shows the results of a test to demonstrate the effectiveness of the canvas jacket method of restraining the animal in the cradle. Curve C/B shows the movement of a steel brace fastened along the spinal cord as related to the movement of the shaker. There is no obvious resonance, nor phase lag of the spinal cord and only a moderate fall in amplitude magnification as the frequency increases. Curves A/B and A/C demonstrate that there is little difference in the amplitude magnification whether the movement of the implant is described relative to the spinal brace or relative to the shaker. In this experiment since the phase shift levels off around 180° the implant oscillates essentially as a simple oscillator. As calculated above the resonance frequency of the implant and its surrounding tissues is approximately 3.6 cycles per second and the damping of the system is approximately one-fifth of the critical value.

Figure 12, on next page, illustrates the data plotted from many separate experiments. An individual experiment can be identified by the type of marker at

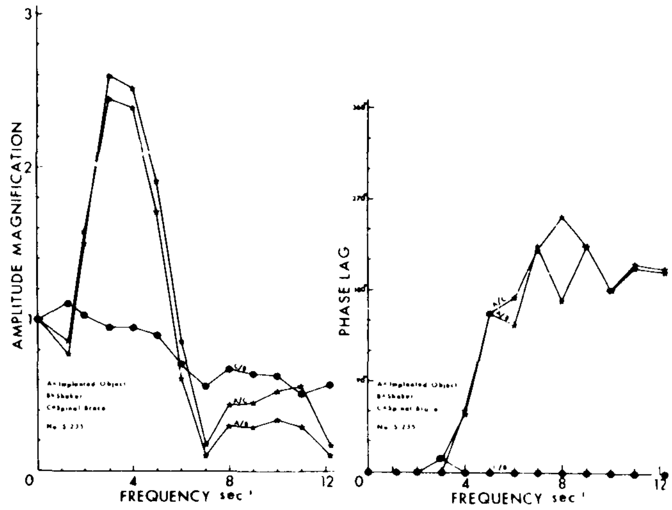

Figure 11. A Check on the Immobilization of the Test Animal.

Data on an experiment testing the effectiveness of the binder restraining the animal on the shaker by comparing the relative movement of implanted object (A), vibrator (B) and the spinal column of animal (C). Amplitude magnification and phase lag are plotted against vibrator frequency.

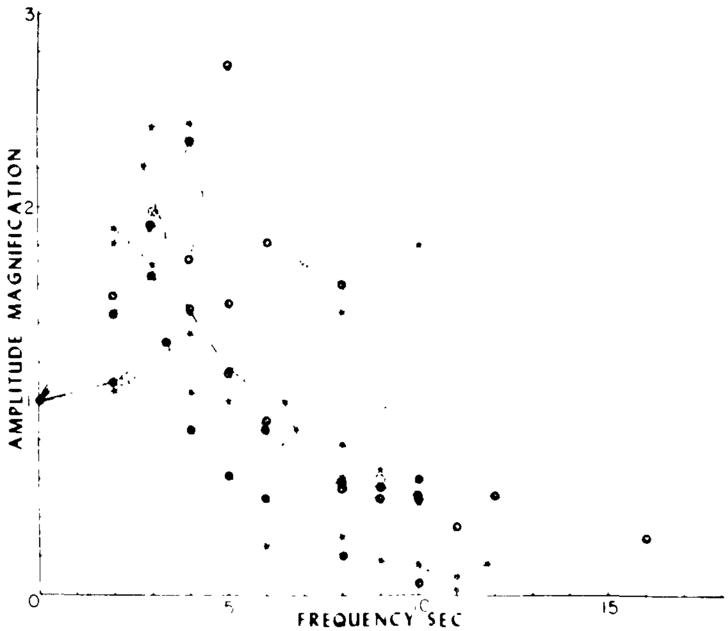

Figure 12. Amplitude Magnification Results.

Amplitude magnification plotted against frequency is shown in this figure. Tests on various dogs (identified by number) of objects implanted in a number of regions (R = ribs, T = thorax, D = diaphragm, I = intestine, K = kidney) are shown.

each experimental point. The letter with each animal number shows the location of the implant, e.g., K = kidney, I = intestine, D = diaphragm, T = thorax (subclavian artery), R = ribs. As in all these experiments the amplitude magnification is computed as the ratio of the implant movement to the shaker movement. In general the lowest frequency showing resonance is in the range of 3 - 5 cycles per second and the corresponding damping is about one-quarter of the critical value. A second resonance frequency appears in many cases in the range of 7 to 10 cycles per second. In all tests illustrated in figure 7 the

double amplitude of the shaker movement was 10 to 12 millimeters in magnitude.

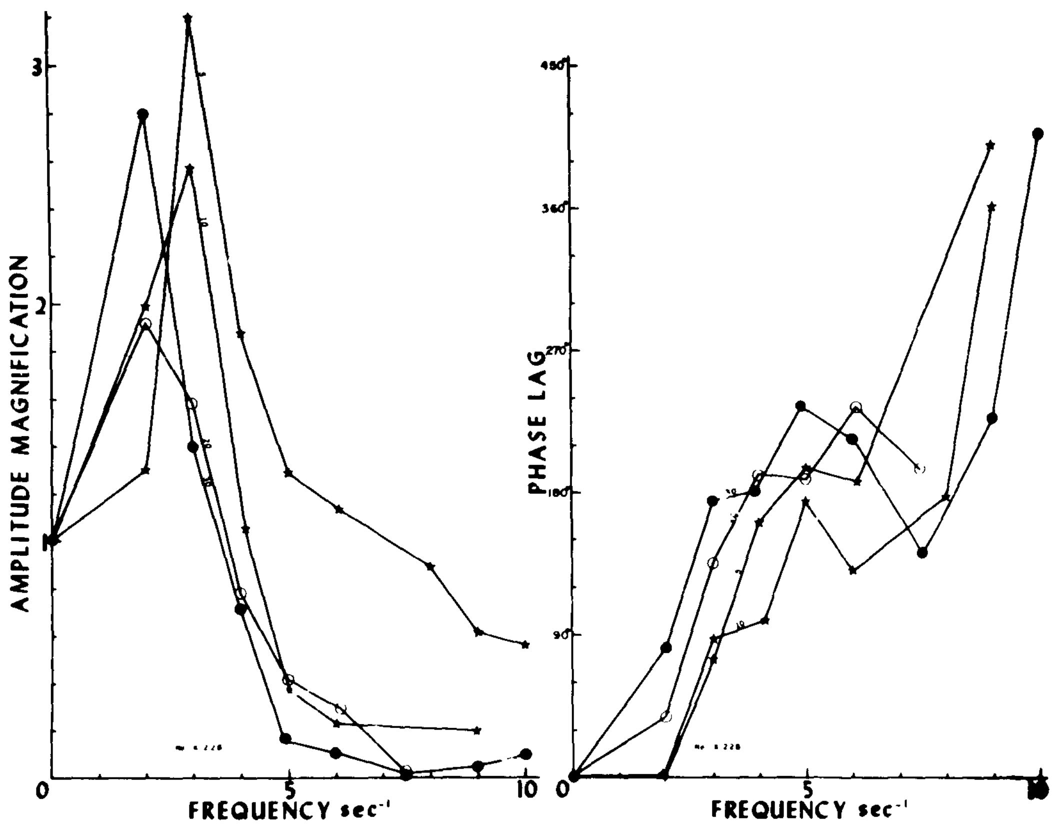

Figure 13. Amplitude Magnification and Phase Lag in Kidney. Variation with Shaker Amplitude.

Graph of test on dog No. 228. The implanted object is on the kidney. This graph, where amplitude magnification is plotted against the vibrator frequency, demonstrates the effect on amplitude magnification of testing the vibration at double amplitude values of 5, 10, 20 and 30 millimeters.

Figure 13 demonstrates the results of an experiment in an animal (no. 228) with an implant on the kidney. The experiment was designed to discover if significant difference in shaking characteristics become apparent when the amplitude of movement of the shaker was varied. Double amplitudes of 5, 10, 20, and 30 millimeters were used. The resonance frequency at 5 and 10 millimeter double amplitude was at about 3 cycles per second. At 20 and 30 millimeters double amplitude the resonance frequency had shifted to about 2 cycles per second. Figure 14 also contains the graph of the phase lag between shaker and implant. The phase shift becomes more than 180° at frequencies above 8 cycles per second. This observation provides evidence of coupling between a simple low frequency oscillator and another system having higher resonance frequency.

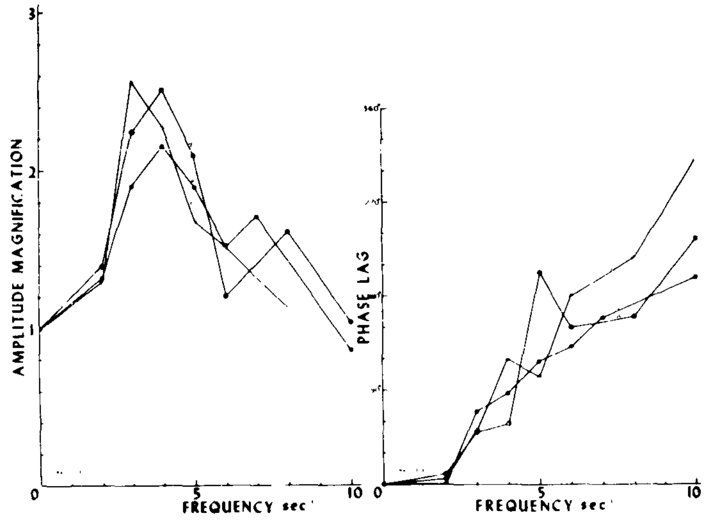

Figure 14. Amplitude Magnification and Phase Lag in Small Intestine. Variation with Shaker Amplitude.

Graph of test on dog No. 213. The implanted object is on the small intestine. This graph, where amplitude magnification is plotted against the vibrator frequency, demonstrates the effect of testing the vibration at double amplitude values of 10, 20 and 30 millimeters.

In figure 14 an opaque object was sutured to the small intestine. In this test a change in the double amplitude of the shaker from 10 and 20 millimeters to 30 millimeters was accompanied by a shift of the resonance frequency from 4 to 3 cycles per second. Some evidence appears for the existence of another resonance frequency between 5 and 10 cycles per second. Coupling of oscillating systems is demonstrated since the phase lag exceeds 180° at the higher frequencies.

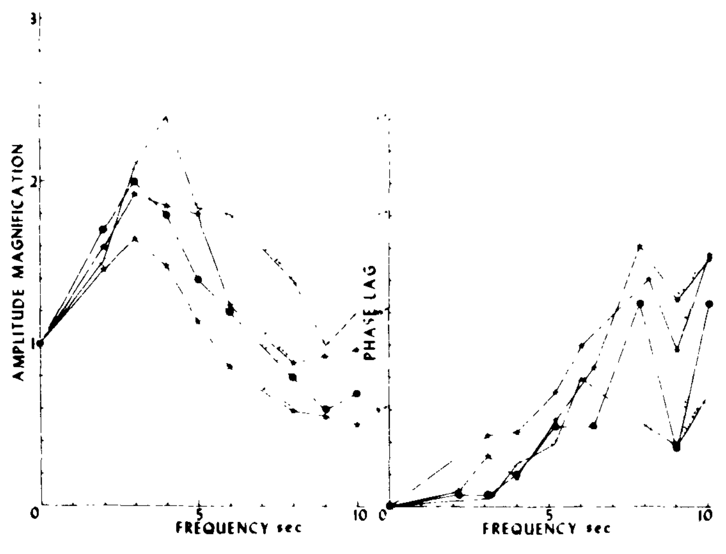

Figure 15. Amplitude Magnification and Phase Lag in Small Intestine and Kidney. Variation with Shaker Amplitude.

Graph of vibration test on dog No. 217. Opaque objects were implanted on kidney (K) and small intestine (I). The vibration tests were performed at two double amplitude values, namely 6 millimeters and 12 millimeters.

The comparison of oscillation behavior of two implants placed in different regions in the abdomen is shown in figure 15. In this test one implant

was made on the small intestine and one on the kidney. The animal was then shaken at double amplitudes of 6 mm and 12 mm. In both regions the resonance frequency decreased from 4 to 3 cycles per second as the double amplitude of the shake increased. The only other point of difference was that the damping from the kidney may be slightly greater than for the intestine.

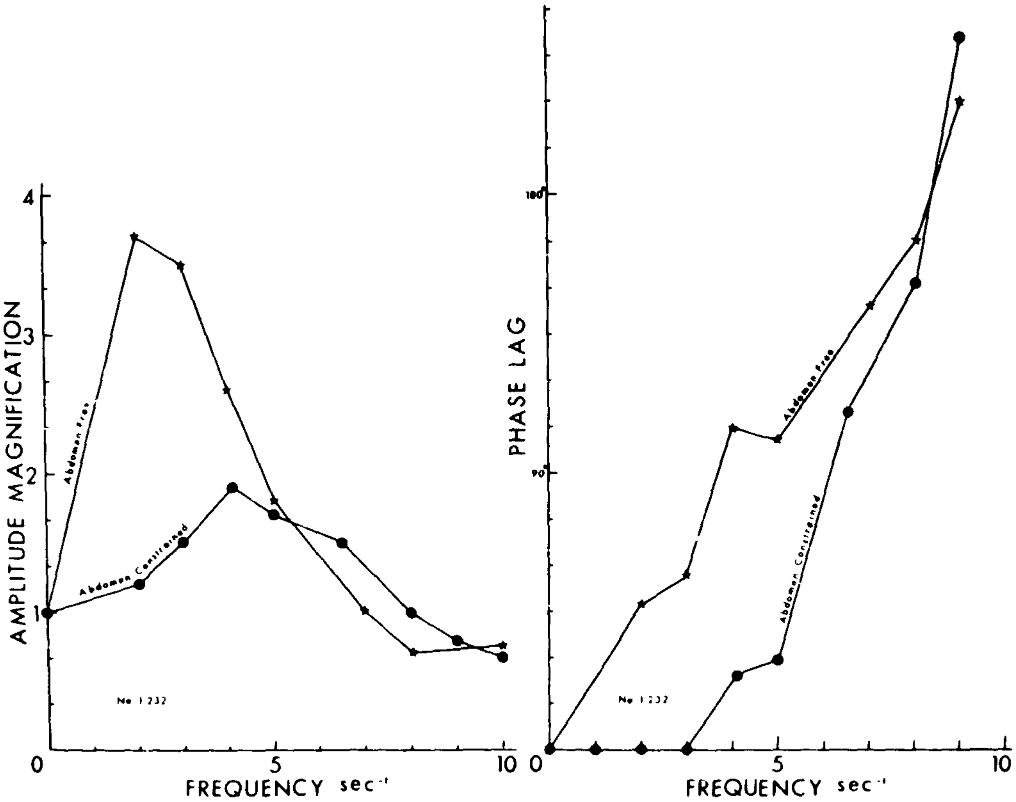

Figure 16. Effect of Abdominal Constraint on Amplitude Magnification and Phase Lag.

Graph to show the effect on an object implanted on the intestine (I) of dog No. 232, of constraining the abdomen by means of a tight binder. The vibrator had a double amplitude of 10 millimeters.

The sources for restoring forces providing the Hooke's Law forces necessary for resonance oscillation are several. One of these could be the abdominal wall. To test this postulate an experiment was performed in which the shaking tests were made with the abdomen as free as usual and then tests were immediately made in which the abdomen was constrained by a tight binder. The results are shown graphically in figure 16. In these tests the double amplitude of the shaker was 12 millimeters. With the abdomen free the

resonance frequency was at 2 to 3 per second with a damping of about 0.15 of the critical value. On constraining the abdomen the resonance frequency rose to 4 cycles per second and the damping increased to 0.30 of the critical value. These changes indicated that much of the flexibility required for low frequency oscillation arises at the abdominal wall. Another constraint upon the motion of the visceral mass may be produced by the pressure of air in the lungs. Several experiments were performed in which the amplitude magnification of the motion of implanted objects was determined under conditions of normal pulmonary pressure and of pulmonary pressure 15 to 20 mm above normal. No experiment showed any detectable shift in the resonance frequency. Hence the pulmonary pressure contributed little to the Hooke's Law constraining force.

DISCUSSION

In the preceding tests it appears that the abdominal and thoracic regions tested in these experiments oscillate as a single mass with a resonance frequency of 3 to 4 cycles per second and a damping of one-fifth to one-quarter of the critical value. The shift toward slightly lower resonance frequencies as the shake amplitude increases may be due to an increase in the effective mass being shaken or to a reduction in the effective constraints which produce the restoring forces on the moving mass. The observation that the phase lag exceeds 180° in many cases indicates that the system is not a simple damped oscillator but rather two or more coupled oscillators.

The lag in phase between the movement of the implanted opaque object and the shaker provides evidence of strain in the coupling of these parts. Reference to figure 6 which shows the relationship between the strain (y-x) and the shaker movement (x) enables one to form some opinion of the relative strain in any circumstance for which the resonant frequency and damping are known. For example, in the experiment discussed previously the values of n_o and δ were respectively 3.6 cycles per second and 0.22. It is apparent then from figure 6 that for frequencies close to zero the relative movement of shaken object and shaker is also close to zero. However, at frequencies near 3.6 cycles per second ($n/n_o = 1$) the relative movement of object and shaker approach 2-1/2 times the movement of the shaker indicating considerable strain. As the frequency of shaking increases above the resonance value the relative movement approaches unity; i.e., the relative movement between object and shaker approaches the full value of the movement of the shaker.

The findings of this investigation on anesthetized dogs are in essential agreement with the results found by measurements of the longitudinal shaking of human subjects. The visceral mass of the abdominal and thoracic contents shakes as a mass having a resonance frequency of 3 to 5 cycles per second and with damping of one-fifth to one-quarter of the critical value. A higher frequency around 7 to 10 cycles per second also appears in many cases. The flexibility for the low frequency resonance of the system lies largely in the abdominal wall. Constraining the abdominal wall raises the resonance frequency since the flexibility is less in the thoracic region. Evidence for the appearance of considerable strain in body tissue is shown when the frequency oscillation is close to the resonance frequency of body regions.

The x-ray method has been found to be useful for determining the resonance

frequency and phase shift of regions of the viscera set in movement by external oscillating forces. The work reported here employed radio-opaque objects of the same specific gravity as the tissues being studied. However, small metal plaques of greater density than the tissues may be attached to any structure so that the movement of specific organs may be studied.

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3. Resonance Frequency
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